

## Early Days of SIS Receivers

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**Abstract.** The modern era of millimeter and submillimeter spectral line observations and interferometry started at the end of 1979 with the invention of the Superconductor-Insulator-Superconductor (SIS) mixer. Tom Phillips co-invented this device while working at Bell Telephone Labs (BTL) in Murray Hill, NJ. His group built the first astronomically useful SIS heterodyne receiver which was deployed on the Leighton 10.4 m telescope at the Caltech Owens Valley Radio Observatory (OVRO) in the same year. Tom Phillips joined the Caltech faculty in the early 1980s where his group continues to lead the way in developing state-of-the-art SIS receivers throughout the millimeter and submillimeter wavelength bands. The rapid progress in millimeter and submillimeter astronomy during the 1980s required developments on many fronts including the theoretical understanding of the device physics, advances in device fabrication, microwave and radio frequency (RF) circuit design, mixer block construction, development of wideband low-noise intermediate frequency (IF) amplifiers and the telescopes used for making the observations. Many groups around the world made important contributions to this field but the groups at Caltech and the Jet Propulsion Laboratory (JPL) under the leadership of Tom Phillips made major contributions in all of these areas. The end-to-end understanding and developments from the theoretical device physics to the astronomical observations and interpretation has made this group uniquely productive.

## 1 Introduction

Receiver development plays a critical role in advancing radio astronomy. This is particularly true at millimeter and submillimeter wavelengths where there is very little commercial or military research. Tom Phillips has played a crucial part in advancing astronomy at these wavelengths by developing new detectors and techniques and using these to make important new observations.

The 1970s were a very active time for millimeter and submillimeter detector development. Groups were pushing the receivers to ever higher frequencies in search of new molecular transitions and better sensitivity. The workhorse receivers at millimeter wavelengths in the 1960s and 1970s were GaAs Schottky-barrier diode mixers. These were whisker contacted semiconductor diodes mounted in waveguides. The whisker inductance, junction capacitance and series resistance made it difficult to match these devices to waveguides over a large bandwidth. The best mixers had noise temperatures at room temperature of  $\sim 300$  K at 115 GHz with 5.5 dB conversion loss (Kerr 1975). Continued development of Schottky-barrier diode mixers throughout the 1970s and early 1980s improved their performance and extended the frequency range in the sub-

millimeter band but with significantly higher noise temperatures at the higher frequencies (Archer 1985).

Keith Jefferts and Tom Phillips developed a new hot-electron detector in 1973 that proved to be very sensitive for spectral line observations (Phillips & Jefferts 1973). This device used InSb as a very fast hot electron bolometer. The noise temperature was 250 K but the instantaneous bandwidth was only about 1 MHz. Lines were observed by sweeping the local oscillator (LO) to cover the spectral range of interest. One of the chief advantages of this detector was that it was a bulk device that could be coupled to waveguides and worked well over a wide frequency range.

Other groups were working on other types of devices such as super-Schottky diode mixers which utilized the superconducting bandgap to improve the noise temperature (Vernon et al. 1977) and Josephson mixers utilizing the very non-linear and very intriguing Josephson-effect for mixing (Taur et al. 1976). These devices were based on very interesting physics but unfortunately did not prove to be useful for astronomical observations.

The field of millimeter and submillimeter astronomy changed dramatically with the invention of SIS mixers. The following sections describe some of the early steps in developing these devices into astronomy receivers that are within a factor of a few of the quantum limit for coherent detectors.

## 2 First SIS Heterodyne Receiver for Astronomy

The Josephson-effect tunneling of cooper pairs through an insulating barrier between two superconductors was a very active research area in the 1970s and many groups were working to understand the physics and making interesting new devices, including mixers (Taur et al. 1976), based on these phenomena. Work in this field lead eventually to SQUID amplifiers, the Josephson voltage standard, ultra-fast logic gates and other interesting devices (Barone & Paterno 1982). Both BTL and IBM were working on the development of Josephson-effect computers which promised to be very fast with low power dissipation. These labs had large projects in superconducting device fabrication and the SIS devices used for the first SIS mixers were a spin off from this effort.

Tom Phillips realized that the small area high current density devices that were being fabricated might also be useful for mixers. Although some thought and effort was spent working on Josephson mixing near zero voltage bias it was soon realized that the very sharp increase in quasi-particle current at the superconducting gap voltage provided a large non-linearity that could be exploited for mixing. A simple classical analysis indicated that these devices would make excellent heterodyne mixers (Torrey & Whitmer 1948; Phillips & Woody 1982).

The group at BTL Murray Hill, NJ put a small area thin film Pb-alloy/-PbOx/Pb-alloy SIS tunnel junction into one of the hot-electron InSb mixer blocks and immediately got favorable results at 115 GHz. The group aimed from the beginning to build a sensitive receiver to measure the CO 1-0 transition at 115 GHz in interstellar molecular clouds. Figure 1 shows electron microscope images of the photolithography shadow mask and an SIS junction fabricated at BTL by Gerry Dolan for use in the first SIS mixer experiments (Dolan 1977). The results were published in Appl. Phys. Lett. in the same issue with results at

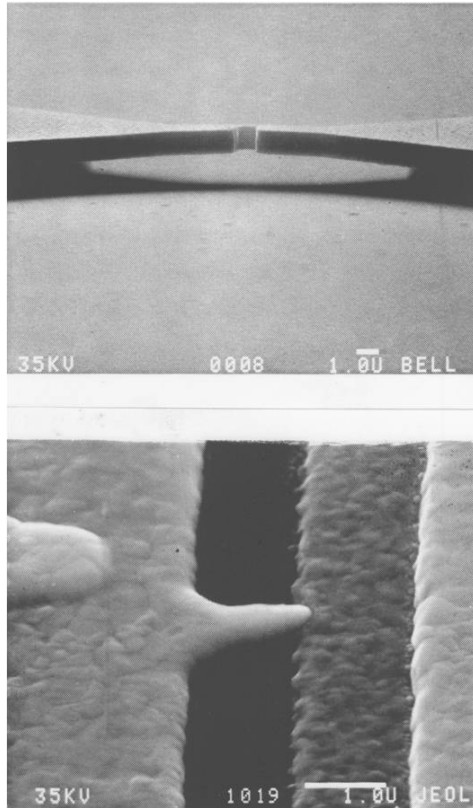


Figure 1. Electron microscope image of shadow mask bridge and sub-micron Pb-alloy SIS tunnel junction fabricated using the mask. The junction is formed by ballistic evaporation of the Pb-alloy for the top and bottom layers from two different angles with the oxide tunnel barrier formed after evaporating the bottom layer.

30 GHz from the U. C. Berkeley group in 1979 (Dolan, Phillips, & Woody 1979; Richards et al. 1979).

Figure 2 shows a schematic of the mixer block and a picture of the mixer and IF amplifier of first SIS heterodyne receiver. Soon after the successful lab tests a complete receiver system was assembled and installed on the Leighton 10.4m telescope at Caltech's Owens Valley Radio Observatory (OVRO) in the late spring of 1979. Figure 3 shows this receiver mounted on the telescope at OVRO. Observations demonstrated that the low receiver noise temperatures measured in the laboratory were correct and that the devices were operating as heterodyne mixers (Phillips et al. 1981).

The early success of this first SIS receiver inspired other research groups to work on SIS receiver development. The field progressed rapidly with many new results reported in the first couple of years (Rudner et al. 1980; Shen et al. 1980).

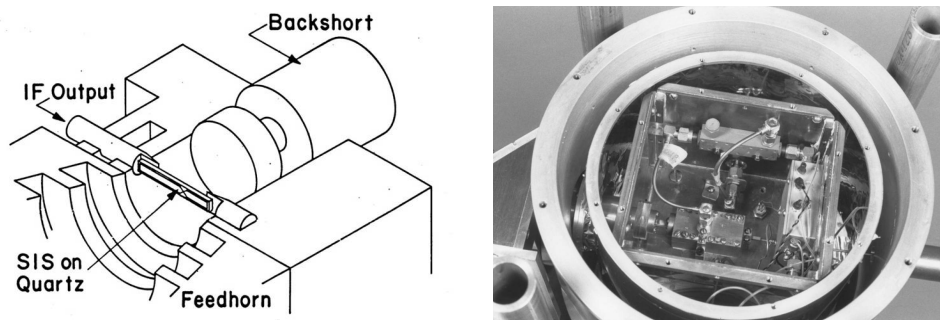


Figure 2. Schematic of the first mixer blocks used for SIS receivers in the left panel and picture of open receiver cryostat in the right panel.

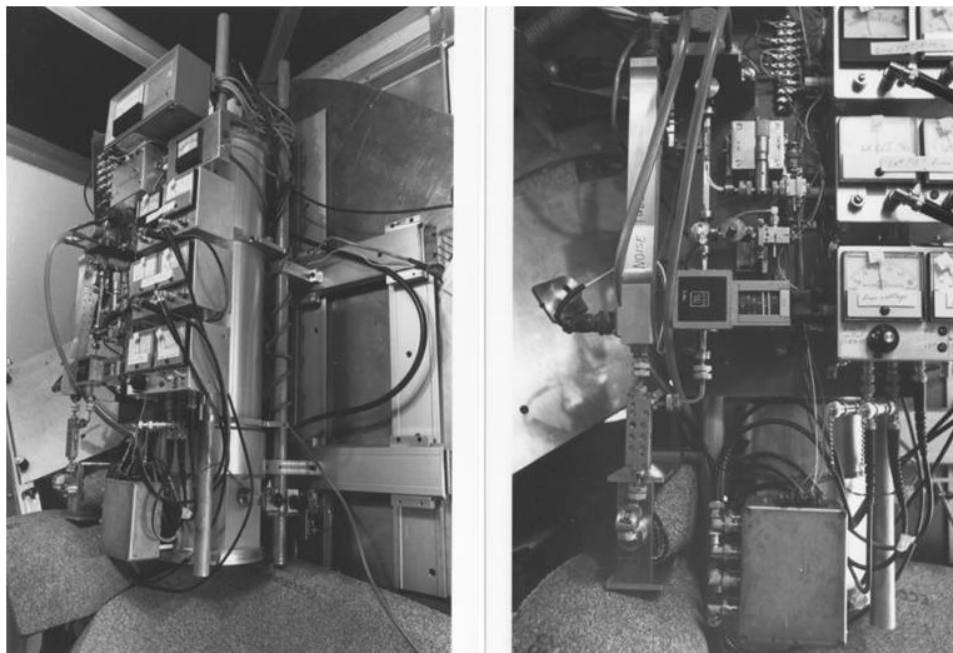


Figure 3. Pictures of the first 115 GHz receiver installed on the Leighton 10.4m telescope at OVRO.

### 3 Device Physics and Theory

Developing a complete theory of the operation of these devices played a critical role in the rapid advances in this field. It was clear that the large non-linearity in the quasi-particle tunneling near the gap voltage would yield good conversion efficiency but that the theory for Schottky-barrier diodes did not apply.

Early work on quasi-particle tunneling at BTL demonstrated photon assisted tunneling which is revealed by step structure in the current vs. voltage at a spacing of  $hf/e$  when CW radiation at a frequency  $f$  is applied (Dayem & Martin 1962; Tien & Gordon 1963). Figure 4 shows a diagram of the superconducting bandgap and photon assisted tunneling for an SIS junction along with

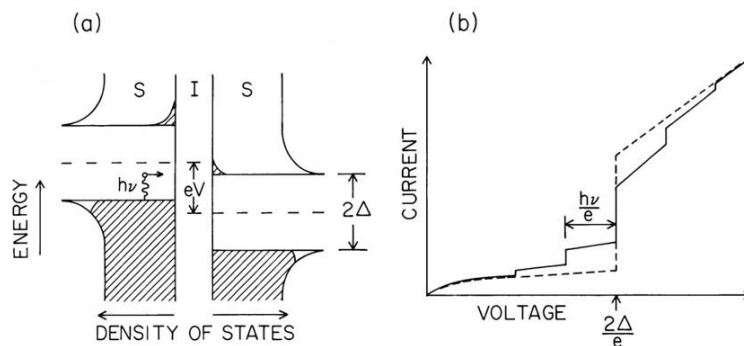


Figure 4. (a) Diagram of the superconducting bandgap and photon assisted tunneling. (b) Idealized current as a function of the voltage. Dotted line is without any radiation and the solid line is with CW radiation applied.

an idealized current vs. voltage characteristic. The quasi-particle tunneling description predicted the current vs. voltage characteristics as a function of the LO drive level and this in turn was used to develop a phenomenological prediction of the mixer conversion efficiency (Phillips & Woody 1982).

The steps in the current vs. voltage relationship were seen in the first mixers (Richards et al. 1979) and are shown in Figure 5 for an SIS receiver operating at 115 GHz. The hot and cold response does not look impressive by today's standards but achieving even this performance for the first generation devices demonstrated the excellent potential for SIS mixers at millimeter wavelengths. A critical issue for SIS mixers was verification that it was the quasi-particle tunneling and not Josephson-pair tunneling that was responsible for the IF output power. A magnetic field is very effective at suppressing the effects of Josephson-pair tunneling. As seen in Figure 5, the IF output power near 0 volts was decreased dramatically when a magnetic field was applied but the output power at the photon steps near the 2.7 mV gap voltage was only slightly changed by the application of a magnetic field. The conversion efficiency and noise temperature actually improved with the application of the magnetic field. Figure 5 also shows that even at 115 GHz the voltage step size is a significant fraction of the superconducting bandgap voltage. As these devices were pushed to higher frequencies the Josephson-pair tunneling became more troubling and new alloy systems needed to be developed for THz receivers.

Tucker's development of the full quantum mechanical description of quasi-particle tunneling and mixing in SIS tunnel junctions was a major advance that enabled a complete description and prediction of both the conversion efficiency and noise (Tucker 1979). This theory showed that the performance of SIS heterodyne mixers is limited only by the added noise imposed by quantum mechanics (Heffner 1962; Caves 1982; Wengler & Woody 1987) and have conversion gains greater than unity, exceeding the limits for classical heterodyne mixing (McGrath et al. 1981; Tucker & Feldman 1985). This theoretical work was quickly incorporated into the receiver design process resulting in well engineered astronomical receivers (Feldman et al. 1983; D'addario 1985). Receiver performance

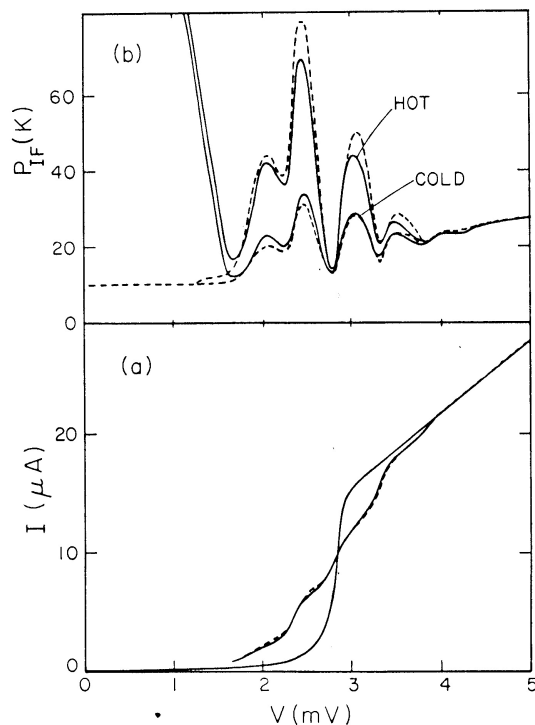


Figure 5. (a) Current vs. voltage characteristic without and with 115 GHz LO applied. (b) IF output power with the receiver looking at a 300 K room temperature load and at a 77 K liquid nitrogen load with the LO on. The solid line is without any magnetic field applied and dashed line is with a magnetic field applied. The photon assisted tunneling is clearly revealed by the modulation in IF power as a function of the bias voltage.

within a factor of a few of the quantum limit for heterodyne mixing became feasible.

#### 4 Device Fabrication

The critical component in SIS receivers is the tunnel junction. The current density, area, gap voltage, leakage current as well as the stability of the thin film materials used are all important for producing reliable astronomical SIS receivers with good performance. The initial devices utilized Pb alloy films and oxide-barriers (Basavaiah & Greiner 1977) and the small submicron junction size was fabricated using a shadow bridge technique (Dolan 1977) as shown in Figure 1. Although these devices could have excellent performance they suffered from aging and thermal cycling failure which made their use in astronomical receivers very difficult.

The widespread adoption of the SIS receivers on radio telescopes required the development of more reliable thin film systems. JPL undertook the task of advancing the fabrication of SIS device when Tom Phillips joined the faculty at Caltech. Most SIS receivers in the millimeter and lower frequency submillimeter band now utilize devices with Nb electrodes and Al-oxide tunnel barriers.

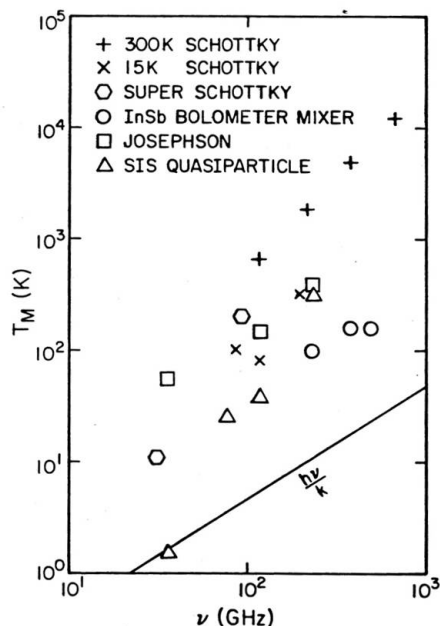


Figure 6. Millimeter and submillimeter receiver results from 1982.

This system produced high quality devices with predictable and stable design parameters with the tuning structures and matching circuits fabricated on the chips along with the SIS device. Excellent performance is achieved throughout the millimeter and submillimeter bands (Zmuidzinis et al. 1998; Kawamura et al. 2000). The group established by Tom Phillips continues to lead in fabricating SIS heterodyne mixer devices and is pushing the devices well into the THz frequency range (Kooi et al. 1998).

## 5 Summary

The groups at BTL, Caltech and JPL under the guidance of Tom Phillips started the field of SIS heterodyne receivers and continue to lead the way in developing astronomical receivers throughout the millimeter and sub-millimeter wavelength range. The rapid advances in millimeter and submillimeter astronomical observations are a direct result of the efforts of this dedicated group of people. Figure 6 shows the performance for the different types of mixers as of 1982. Only a few years after the invention of SIS receivers they exceeded the performance of the previous mixer technologies. SIS mixers have now displaced essentially all other receivers in the frequency range from 120 GHz to 1 THz.

The contributions of the researchers working under Tom's leadership span the range from device physics and fabrication to construction and operation of the telescopes used for the astronomical observations as well as the observations

themselves and the astrophysical interpretation of the measurements. This fully integrated approach has proven to be extremely beneficial.

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